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IMPACT STRENGTH AND TOUGHNESS OF FIBER COMPOSITE MATERIALS.(U)
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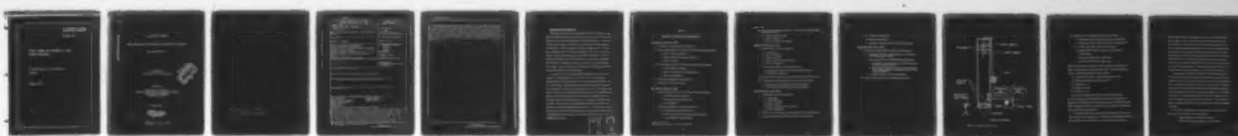

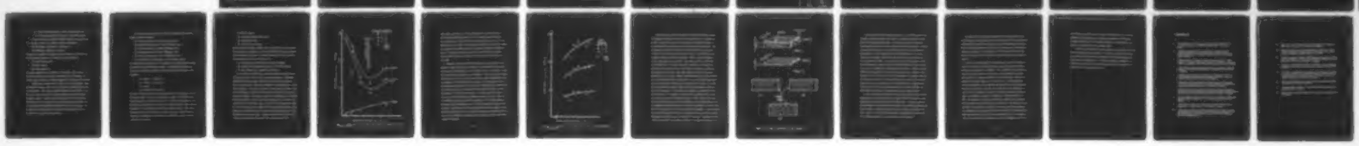

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ILLINOIS INSTITUTE OF TECHNOLOGY
CHICAGO

JANUARY 1977

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FINAL SCIENTIFIC REPORT

IMPACT STRENGTH AND TOUGHNESS OF FIBER COMPOSITE MATERIALS

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Submitted by

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Specimens in the shape of rectangular cross section beams were prepared and tested. The following varibles have been studied: Specimen geometry, Impact velocity, Effect of notch, and Orientation of lamination planes with respect to impact load. The failure was observed using a high speed movie camera and the movies were analyzed to determine and create a model of the fracture process. The studies had shown that glass fiber reinforced epoxies are rate sensitive when an impact load is applied to them. The mechanism of absorbing energy is delamination between layers and between fibers, thus, the type of glass fiber does not change

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the toughness of the material. It was found that the orientation of the lamination plies with respect to the impact load direction will have a great influence on the mode of fracture and energy absorption. The studies with the carbon fiber composites reveal the brittle nature of this material, particularly when compared to the glass fiber composites. Additional research was accomplished in four general areas: Impact property study of angle-ply laminates, Optimization of impact properties of hybrid composites, Effect of Interface strength of impact of glass fiber laminates, and Study of energy absorbing mechanisms in glass fiber composites.

I. RESEARCH ACCOMPLISHMENTS

The original contract was initiated November 1, 1971 and a number of significant accomplishments have been made during the resulting time period. The results of the first 12 months have been described in Technical Report No. 1. The results for the second year (Nov. 1972 through Nov. 1973) and for the third year (Nov. 1973 through Nov. 1974) are discussed in Technical Reports 2 and 3. Technical Report 4 discusses some of the results accomplished in the 4th year. The research program has thus far benefited from the presence of Dr. Assa Rotem in 1971 and Professor Jacob Lifshitz in 1972, both of whom are on the faculty of the Technion, Israel Institute of Technology, and have spent one year each at Illinois Institute of Technology. Also, in 1975-76, Mr. Avraham Mazor, of the Ministry of Defense in Israel, participated in the research program.

A summary of the significant accomplishments during recent years is shown in Table 1. A brief discussion will now follow. In the first year, equipment required to perform drop weight impact tests was completed and thoroughly checked out. We also have a Charpy-Izod-Tension impact testing machine, a high speed ball impact machine and high strain rate testing machine which can simulate impact testing. Furthermore, an instrumented Charpy impact machine was added during the second year and is being utilized in the current studies. The apparatus which was constructed to perform drop weight impact tests in bending is shown schematically in Figure 1. The machine has been designed so that a high speed camera can be used from the side to photograph the process of fracture. A Hycam model 41-0005 high speed movie camera was purchased during the second year and is being utilized to photograph fracture during impact. The maximum framing rate of this camera is 22,000 frames per second.

TABLE 1

SUMMARY OF RESEARCH ACCOMPLISHMENTS

Year 1 (Nov. 1971 - Nov. 1972)

I. Construction of Drop Weight Impact Machine

II. Study of Impact Behavior of Unidirectional and Crossply Glass Laminates

A. Effect of Specimen Geometry

B. Effect of Impact Velocity* and Impact Mass

C. Effect of Notches

III. Study of Impact Behavior of Unidirectional Carbon Fiber Composites

A. Effect of Specimen Geometry

B. Effect of Impact Velocity and Impact Mass

C. Effect of Fiber Modulus

IV. High Speed Photographic Studies of Impact

V. Proposed Laminate Failure Model

Year 2 (Nov. 1972 - Nov. 1973)

I. Study of Impact Behavior of Hybrid Carbon-Glass Fiber Composites

A. Effect of Ply Stacking Geometry

B. Instrumented Charpy Impact Studies

C. Fracture Model

II. Study of Impact Behavior of Angle-Ply Laminates

A. Instrumented Charpy Impact Studies

B. Effect of angle of fibers on impact energy and strength

C. Fracture Model and Impact Damage

*Maximum impact velocity in all cases is 22 ft/sec.

Table 3 (Cont.)

III. Study of Energy Absorbing Mechanisms in Glass Fiber Composites (Random Discontinuous Fibers)

A. Effect of Matrix Properties

B. Effect of Interface

C. Fracture Toughness Test Methods

Year 3 (Nov. 1973 - Nov. 1974)

I. Impact Behavior of Hybrid Composites

A. Glass-Carbon

B. Kevlar-49-Carbon

C. Glass - Kevlar 49

D. Effect of Interlaminar Shear Strength

E. Effect of Temperature

II. Study of Impact Behavior of Angle-Ply Laminates

A. Development of Failure Model for Glass Fiber Composites

B. Carbon Fiber Composites

III. Effect of Interface Treatment on Impact Behavior of Glass Fiber Laminates

IV. Study of Energy Absorbing Mechanisms in Glass Fiber Composites

A. Definitions and Test Methods for Fracture Toughness

B. Theoretical Prediction Methods for Energy Absorption

Year 4 (Nov. 1974 - Nov. 1975)

I. Impact Behavior of Hybrid Composites

A. Glass-Carbon

B. Kevlar-49-Carbon

C. Glass - Kevlar 49

D. Effect of Interlaminar Shear Strength

E. Effect of Temperature

II. Effect of Interface Strength on Impact Behavior of Glass Fiber Laminates

III. Study of Energy Absorbing Mechanisms in Glass Fiber Composites

A. Oriented Fiber Composites

B. Random Fiber Composites

C. Comparison of Experiment with Theoretical Calculations

Year 5 (Nov. 1975 - Nov. 1976)

I. Environmental Exposure Effects on Carbon Fiber Composites

A. Evaluation of 11 Years of Water Exposure on a Carbon-Epoxy and Graphite-Epoxy Composite

B. Environmental Effects on a T300/SP313 (Epoxy) Composite

i. Water diffusion studies in epoxy matrix including the effect of stress on moisture diffusion

ii. Water diffusion studies in unidirectional lamina to characterize diffusion parallel and perpendicular to fiber. Effect of stress on diffusion.

iii. Effect of moisture on mechanical properties

II. Effect of Interface Strength on Composite Impact Behavior

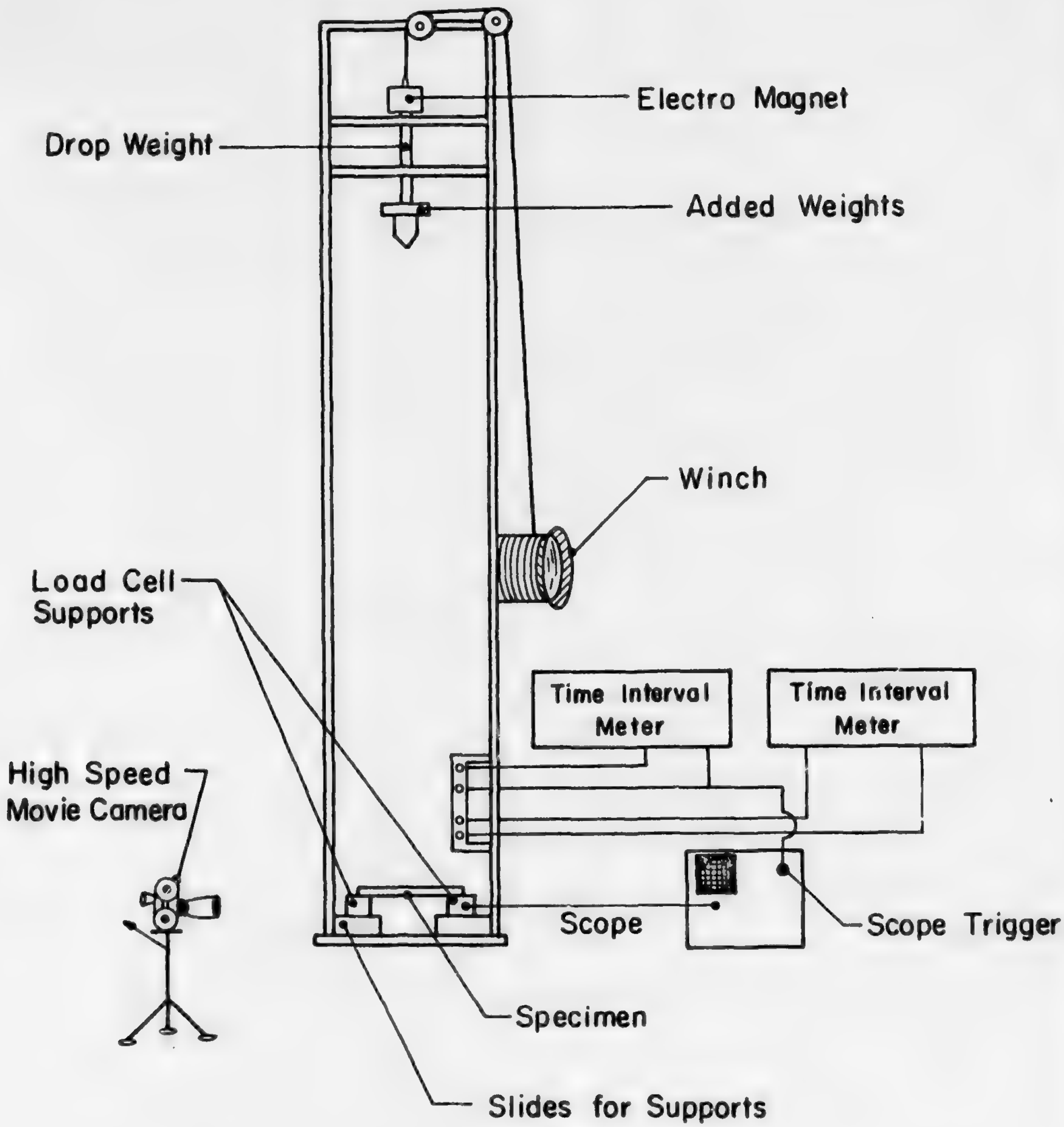

Figure 1. Drop Weight Impact Tester.

During the first year the following laminates were studied:

1. Scotchply type 1002 (E glass-epoxy resin) 25 plies (crossply)
2. Scotchply type 1002, 25 plies (1-2-19-2-1) with 4 plies at 90°
3. Scotchply type 1002, 25 plies all unidirectional
4. Scotchply XP251 S (S glass in epoxy matrix) (18 plies, all unidirectional).
5. Carbon fibers (HMS) 25 plies, epoxy matrix
6. Carbon fibers (HTS) 28 plies, epoxy matrix

Specimens in the shape of rectangular cross section beams were prepared and tested. The specimens were impacted at their center in the drop weight impact machine. The following variables have been studied:

(1) Specimen geometry (span: thickness and width: thickness)
(2) Specimen support (fixed ends and free ends)
(3) Impact velocity
(4) Weight of indentor
(5) Effect of notch
(6) Orientation of lamination planes with respect to impact load

In all cases the energy absorbed during impact was calculated as well as the strength of the material from the oscilloscope readings. The failure was observed using a high speed movie camera and the movies were analyzed to determine and create a model of the fracture process.

The studies had shown that glass fiber reinforced epoxies are rate sensitive when an impact load is applied to them. This fact must be considered when testing such materials or when extrapolating test results to predict actual performance. A

common impact test such as the Charpy test cannot give complete information since it supplies a constant amount of energy for totally different specimens some of which may absorb most of the energy which is applied to them. The strength and energy absorbed during impact was found to increase with increased rate of loading. The mechanism of absorbing energy is delamination between layers and between fibers, thus, the type of glass fiber does not change the toughness of the material. It was found that the orientation of the lamination plies with respect to the impact load direction will have a great influence on the mode of fracture and energy absorption. High speed movies were taken of the various impact tests and a model to describe the fracture process was developed.

The studies with the carbon fiber composites reveal the brittle nature of this material, particularly when compared to the glass fiber composites. Impact failures of carbon fiber composites were also recorded with high speed photography. Contrary to glass fiber composites there was only a slight increase in strength with loading rate. The value of energy absorption for the carbon fiber composites is an order of magnitude less than that for glass fiber composites. The calculated value of ealstic strain energy absorbed for the carbon fiber composites is much nearer the measured value than for glass fiber composites. This results from the absence of delamination and other fracture modes in the case of the carbon fiber composites.

The research accomplished during the second, third and first half of the fourth year can be divided into four general areas:

I. Impact property study of angle-ply laminates

II. Optimization of impact properties of hybrid composites

III. Effect of Interface strength on impact of glass fiber laminates

IV. Study of energy absorbing mechanisms in glass fiber composites

In area I, Scotchply Type 1002 laminates (E-glass in epoxy matrix) of 3M Co. was used in the form of two different laminate configurations -

(1) $[0/90/0_4/0]_S$, designated as "Unidirectional"

(2) $[(0/90)_3/0]_S$, designated as "Crossply"

Specimens in the shape of rectangular beams have been used to study the effect of the following variables on the impact strength of the laminates:

(1) fiber orientation angle

(2) impact velocity

(3) specimen geometry

The impact experiments were performed on a drop-weight impact machine. The load-time response during the impact was monitored on an oscilloscope. The impact energy was found to be strongly dependent on the geometry of the specimen.

Another aspect of research area I was the study of impact damage. Impact specimens were tested in static flexure to measure the residual strength and modulus after impact. Both single and repeated impacts have been studied. It was found that in some cases, both the residual strength and modulus are severely affected by impact. Dynamic modulus and damping ratio were also measured after impact in order to quantify the extent of damage induced after each drop. A Bruel and Kjaer Complex Modulus Apparatus was used for this purpose. The measurements will help establish the damage initiation energy which is more important than a single impact energy value.

In area II, the materials (purchased in the form of prepregs) which are being studied included the following:

(1) E-glass unidirectional in Fiberite 934 epoxy matrix

(2) Thornel-300 graphite fiber in Fiberite 934 epoxy matrix

(3) Kevlar-49 organic fiber in Fiberite 934 epoxy matrix

(4) GY-70 graphite fiber in Ferro CE-9006 epoxy matrix

(5) Kevlar-49 organic fiber in Ferro CE-9006 epoxy matrix

(6) Style 1543 woven E-glass fabric in Ferro E-293 epoxy matrix

The material selection was based on the consideration of variables like fiber strength, fiber modulus, and interlaminar shear strength. The prepregs were combined in a wide variety of lamination configurations, which can be classified into four broad categories:

(a) sandwich - unidirectional

(b) alternate - unidirectional

(c) crossply

(d) combination of (b) and (c)

The choice of these configurations were made on the basis of a preliminary study with HMS graphite and style 1543 woven E-glass fabric prepregs. The composite plates were fabricated by a press lamination technique. The static flexure properties were measured and the failure modes were identified. Unnotched Charpy impact tests were performed on an instrumented Tinius Olsen impact testing machine. One of the advantages of using instrumented impact tests is that a continuous dynamic load-time and energy-time response can be obtained on an oscilloscope. Thus the following properties can be measured:

(1) dynamic strength

(2) total energy absorbed during impact

(3) initial fracture energy

(4) post-initial fracture energy

Some of the hybrid composites tested to date have improved the impact strength of low-impact graphite composites by as much as 40-60 times without any significant sacrifice of stiffness or strength. This experimental program has provided a basis for more fundamental work in the future, such as

(a) active energy absorbing mechanisms in hybrid composites

(b) correlation of basic material properties with the hybrid properties

(c) impact damage study - damage initiation energy

During the fourth and fifth years studies were performed to study the effect of interface strength on impact behavior of glass fiber laminates. Specifically, glass fabric laminates have been constructed using a heat cleaned glass fabric as well as several surface treated fabrics designed to provide laminates with various interface strengths. It has been shown that the total impact energy (Charpy impact) can be maximized by reducing the interlaminar shear strength of the composite to values below 4000 psi. For example, in Figure 2 the impact energy vs. interlaminar shear strength (ILSS) is shown for a polyester-glass laminate. It can be seen that a minimum value of total impact energy occurs at an ILSS of approximately 4000 psi. For ILSS values greater than 4000 psi, the failure mode changes from primarily delamination to fiber fracture and as a result increasing values of ILSS now cause increasing values of impact energy. It should be noted that the initiation value of impact energy increases monotonically with increasing values of ILSS. In the

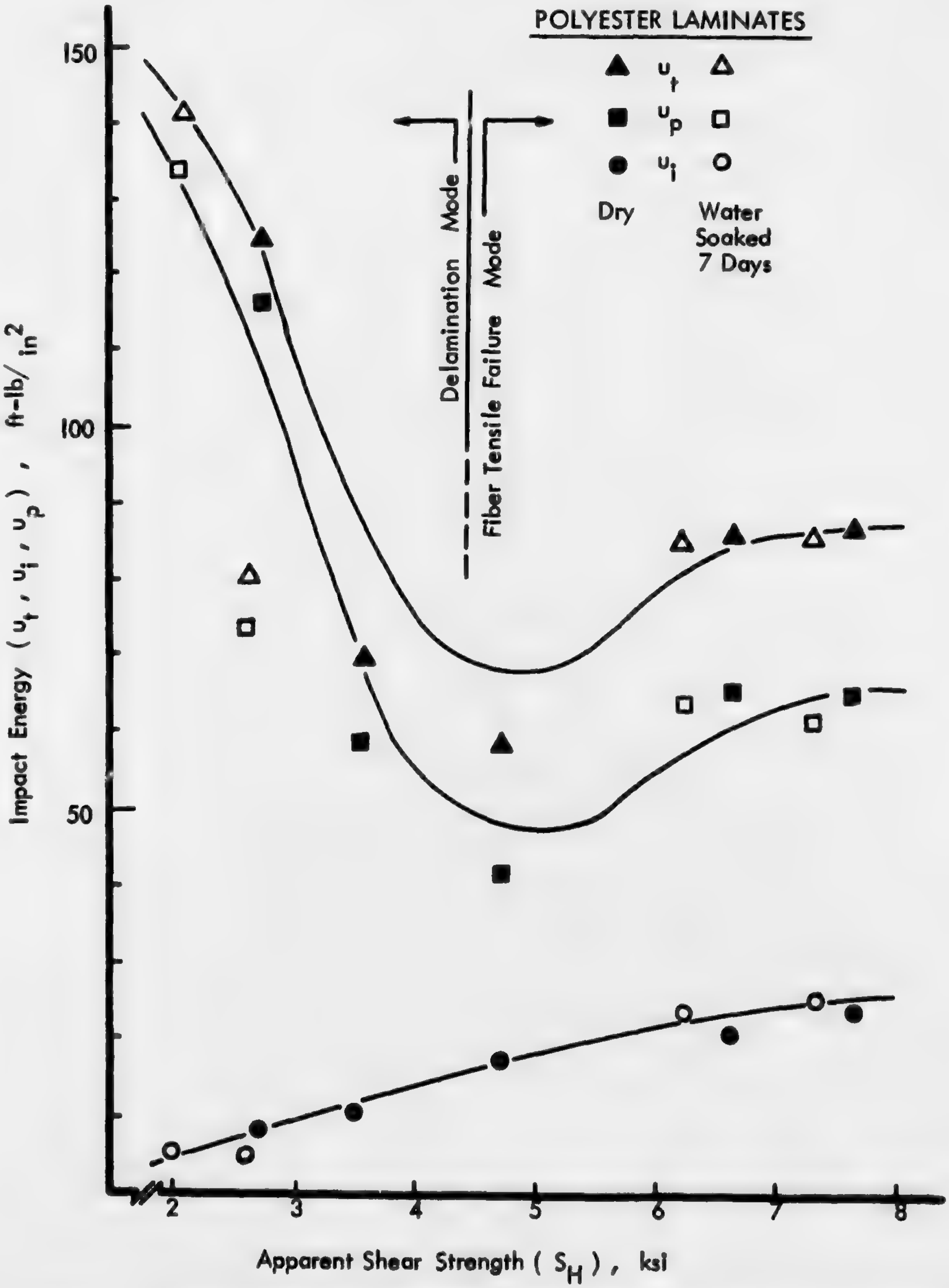

Figure 2. Impact Energy vs. Short Beam Shear Strength of Fiberglass-Reinforced Polyester Laminates

case of epoxy resin laminates, the total impact energy is shown to increase with increasing ILSS (see Figure 3) because it was not possible to reduce the ILSS to a low enough value to induce delamination as a primary failure mode. It was also concluded that the increase in impact energy with decreasing values of ILSS resulted from greater amounts of delamination area as opposed to altering the delamination energy. The exposure of specimens to 7 days of water altered the interlaminar shear strength but as shown by Figures 2 and 3 the results could be plotted on the same graph.

Fundamental studies to determine the mechanisms in the composite most responsible for energy absorption were continued. It was decided that to most effectively study material parameters, such as the effect of matrix and interface, a random fiber discontinuous composite should be investigated. Since these composites possess planar isotropy, the use of existing fracture mechanics tests and methodology should be appropriate, with only modifications necessary in the interpretation of results. These studies are fundamental to a more complete understanding of the energy absorption mechanisms occurring during impact fracture and thus eventually can lead to optimization of the material to resist impact. The initial studies have been very successful in determining the type of damage occurring at the tip of a crack and in establishing methods to measure fracture toughness. A new fracture toughness parameter has been defined based on the initiation of debonding between the fiber and matrix. Experimental values of energy absorption have been compared to theoretical calculations for the various composites fabricated with reasonable agreement. Thus, it may be feasible to determine the relative importance of the various energy absorption mechanisms.

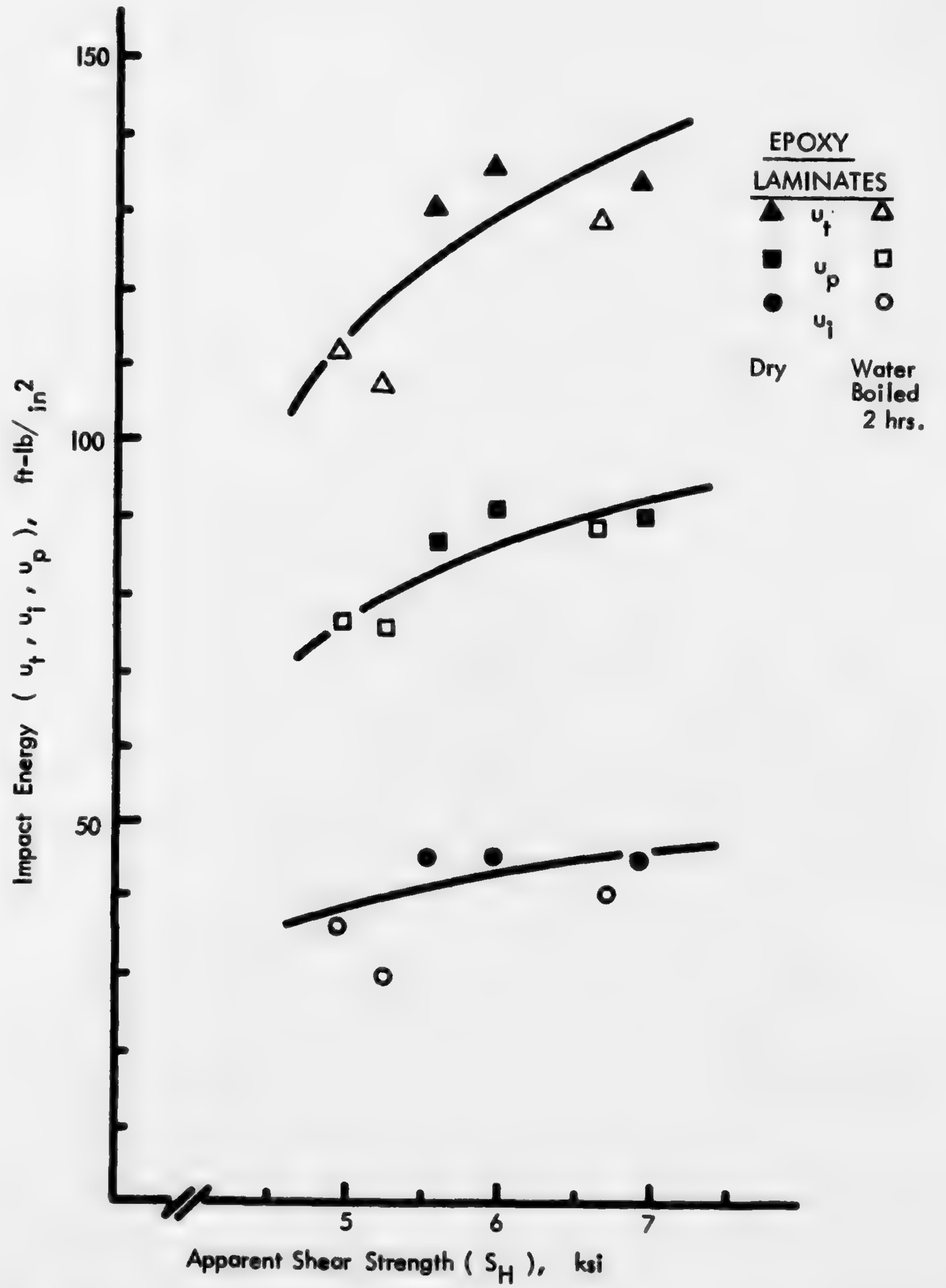

Figure 3. Impact Energy vs. Short Beam Shear Strength of Fiberglass-Reinforced Epoxy Laminates

During this year, studies were initiated on the moisture diffusion mechanism in carbon fiber composites as well as in the unreinforced resin. The research was primarily directed to study the relative contributions of interface and matrix on the overall lamina moisture diffusion and their relative effect on properties. Specimens having different fiber orientations were machined from plates, as shown in Figure 4, so as to allow selective diffusion to occur. The cut specimens were exposed to different environmental conditions: 98% R.H. and full immersion in water at room temperature and at 60°C. The validity of Fick's law for diffusion was first determined. The percent weight gain was plotted as a function of the square root of the exposure time and a clear linearity was found up to fractional weight gains of 0.65 to 0.80. Upon higher temperature exposure, the moisture diffusion rate and the moisture diffusion coefficients increased as could be expected. Since we determined the moisture absorption rate only at two different temperatures, the activation energy for diffusion and the permeability index have not been determined, and the overall diffusion coefficient has not been expressed as a function of these two parameters. A reverse effect of temperature on equilibrium moisture content was found. The equilibrium amount of moisture absorbed by all the specimens was higher at the lower temperature exposure. These results fit Augl's study and might be explained by the moisture desorption during the weighing period which is intensified at higher temperatures, as discussed in the background. However, more efforts will be placed in order to fully investigate this phenomenon. It was also found that for the same temperature condition, the equilibrium moisture content was higher for complete immersion in water, than for 98% R.H. exposure. Nevertheless, smaller values were obtained for the diffusion coefficients for completely immersed specimens.

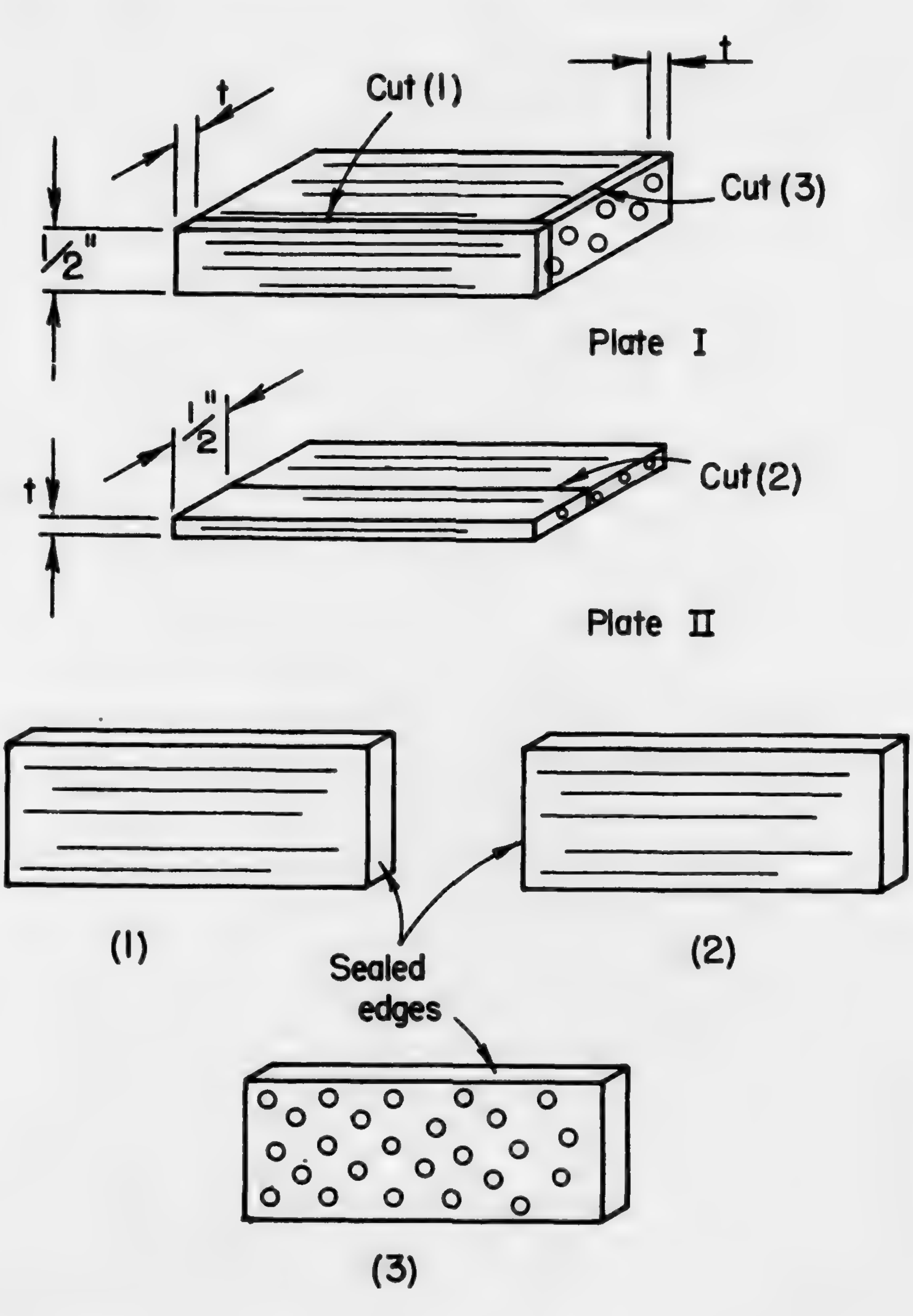

Figure 4. : Fiber orientation to be tested

An evident effect of fiber orientation was found. In the case of unidirectional specimens, diffusion coefficients were found to be around 3 times greater for those specimens having fibers perpendicular to the surface of exposure, as compared to those longitudinal specimens with fibers parallel to the surface of exposure. Balanced crossply specimens behaved in a fashion essentially similar to those unidirectional fiber specimens. These preliminary results have indicated that there is a strong influence of the interface, reflected by fiber orientation in our experiments, on the overall moisture diffusion. Hence, the study on the effect of interfaces as well as the fiber orientation effects on the lamina moisture absorption will be intensified in the next year, as discussed in the proposed research section. In order to study the effect of machined surfaces, a 2 mm thick plate was machined by milling to a final thickness of 1 mm. Specimens were cut from the plate and were exposed to the same environmental conditions. It has been concluded that the quality of the surface of exposure seems to have an effect on the moisture diffusion rate. Exposed surfaces which had a resin rich layer (as molded) yielded smaller values for diffusion rate and diffusion coefficients, as compared to specimens with machined surfaces.

A study on the static tensile stress effect on moisture diffusion was also started. Longitudinal and transverse specimens were loaded to 50% of the ultimate and were exposed to the same humid environments described earlier. It should be noted that more modification in the test technique is needed in order to determine quantitatively the stress effect on moisture absorption upon long term exposure to humid environments. However, the results have clearly shown a considerable effect of the stress on the moisture absorption rate, even after only short term exposure.

In order to study the deformational response to moisture absorption, dimensional changes of the exposed specimens to environmental conditions were conducted. The dimensional changes of the specimens as moisture is absorbed have shown essentially a linear relationship except for the initial weight gain where no dimensional changes were detected. This is probably due to the filling up of pores and voids, where no swelling process is taking place and may be representative of the material quality.

In order to be able to predict material performance under real-life exposure to humid environments, the effect of dynamic exposures and long time exposure to humid environments should be investigated. Thus, the effects of long term exposure to dry and humid environments on carbon-epoxy and graphite-epoxy composites have been studied. Filament wound NOL rings were fabricated in 1965 and were placed in dry, distilled water and sea water for 11 years. Moisture desorption tests were conducted in order to determine the water content of specimens exposed to the water environments. The effect of the history on moisture absorption characteristics was investigated by reexposure of partially and completely dried specimens to two different environments: distilled water at 60°C and 98% R. H. at 60°C. The weight gain was measured and diffusion coefficients were calculated. Horizontal shear tests and flexural tests were performed on "wet" specimens (current properties) and on partially and completely dried specimens (residual properties). A considerable shear strength reduction (current and residual) was found for carbon-epoxy specimens having humid long term environmental history. This strength reduction might indicate that microdamage and irreversible degradation of the matrix

and interfaces occurred during the 11 years of water immersion. The strength degradation has been qualitatively correlated and interpreted with the moisture absorption characteristics. No irreversible damage in the fiber properties was observed as concluded from flexural strength results.

The shear strength of graphite-epoxy composites was considerably lower than that found for carbon-epoxy composites. Also, the current strength of wet specimens having humid history exposure was higher than the reference and than the strength found in dried specimens. This higher wet strength is probably due to internal stress relaxation in the case where shear strength is dominated by interfacial failure rather than by matrix failure.

II. PUBLICATIONS

1. "Impact Resistance and Toughness of Fiber Reinforced Plastics", Fifth St. Louis Symposium on Advanced Composites, April 1971 (with A. Rotem).

2. "Impact Strength and Fracture of Carbon Fiber Composite Beams", Proceedings 28th Technical and Management Conference, Reinforced Plastics/Composites Div. of Society of Plastics Industry, February 1973 (with A. Rotem).

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5. "Impact Properties of Laminated Composites", Proceedings of 30th Technical Conference, Reinforced Plastics/Composites Division, Society of the Plastics Industry, Feb. 1975 (with P. Mallick).

6. "Optimization of ImpactProperties of Hybrid Composites," Proceedings of the 30th Technical Conference, Reinforced Plastics/Composites Division, Society of the Plastics Industry, Feb. 1975 (with P. Mallick).

7. "Strength and Fracture Properties of Random Fiber Polyester Composites", Proceedings of the 30th Technical Conference, Reinforced Plastics/Composites Division, Society of the Plastics Industry, Feb. 1975 (with S. Gaggar).

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13. "Fracture Toughness of Random Glass Fiber Epoxy Composites: An Experimental Investigation", presented at Tenth National Symposium on Fracture Mechanics", ASTM, Aug. 1976 (with S. Gaggar).

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17. "Moisture Diffusion Studies in a Graphite Reinforced Epoxy Lamina" (in preparation with J. Belani).

18. Effect of Stress on Moisture Diffusion in Epoxy Resins (in preparation with G. Waring).